

GLOBAL ENERGETICS OF SEVERAL LARGE SOLAR ERUPTIVE EVENTS

A. G. EMSLIE¹, B. R. DENNIS², A. Y. SHIH², P. C. CHAMBERLIN², R. A. MEWALDT³,
C. S. MOORE⁴, G. H. SHARE⁵, A. VOURLIDAS⁶, AND B. T. WELSCH⁷

ABSTRACT

We have evaluated the energetics of 38 solar eruptive events observed by a variety of spacecraft instruments between February 2002 and December 2006, as accurately as the observations allow. The measured energetic components include: (1) the radiated energy in the GOES 1 – 8 Å band; (2) the total energy radiated from the soft X-ray (SXR) emitting plasma; (3) the peak energy in the SXR-emitting plasma; (4) the bolometric radiated energy over the full duration of the event; (5) the energy in flare-accelerated electrons above 20 keV and in ions above 1 MeV; (6) the kinetic and potential energies of the coronal mass ejection (CME); (7) the energy in solar energetic particles (SEPs); and (8) the amount of free (nonpotential) magnetic energy estimated to be available in the pertinent active region. Major conclusions include: (1) the energy radiated by the SXR-emitting plasma exceeds, by about half an order of magnitude, the peak energy content of the thermal plasma that produces this radiation; (2) the energy content in flare-accelerated electrons and ions is sufficient to supply the bolometric energy radiated across all wavelengths throughout the event; (3) the energy contents of flare-accelerated electrons and ions are comparable; (4) the energy in SEPs is typically a few percent of the CME kinetic energy (measured

¹Department of Physics & Astronomy, Western Kentucky University, Bowling Green, KY 42101
emslieg@wku.edu

²Code 671, NASA Goddard Space Flight Center, Greenbelt, MD 20771
brian.r.dennis@nasa.gov, albert.y.shih@nasa.gov, phillip.c.chamberlin@nasa.gov

³California Institute of Technology, Pasadena, CA rmewaldt@ssl.caltech.edu

⁴Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO
christopher.moore-1@colorado.edu

⁵Department of Astronomy, University of Maryland, College Park, MD share@astro.umd.edu

⁶Code 7663, Naval Research Laboratory, Washington, DC vourlidas@nrl.navy.mil

⁷Space Sciences Laboratory, University of California, Berkeley, CA welsch@ssl.berkeley.edu

in the rest frame of the solar wind); and (5) the available magnetic energy is sufficient to power the CME, the flare-accelerated particles, and the hot thermal plasma.

Subject headings: Sun: activity – Sun: coronal mass ejections – Sun: flares – Sun: particle emission – Sun: X-rays, gamma rays

1. Introduction

Solar eruptive events (SEEs), which are comprised of flares and associated coronal mass ejections (CMEs), are the most energetic manifestations of conversion of magnetic energy in the solar system. Over a period of tens of seconds to minutes, they can convert upwards of 10^{32} ergs of energy carried in non-potential, current-carrying magnetic fields into accelerated particles, heated plasma, and ejected solar material.

While the overall energy involved in an SEE is not in serious doubt, its partition amongst its component parts has so far been estimated only for a few events. In this paper, we provide the first statistical analysis of energy partition throughout the various manifestations of an SEE, for thirty-eight large events. We provide this information not only to establish “typical” ratios of the energy in various components of the event, but also to provide some idea of the range over which such ratios extend, and we especially point out events in which the strength of one component or another appears to lie outside the norm. We offer this analysis with the goal of providing useful constraints for modelers of the energy release process(es) involved.

This paper grew out of the energetics working group at the meeting on “Solar Activity during the onset of Solar Cycle 24” held in Napa, CA, from December 8 - 12, 2008. It is a continuation of the work begun at the Taos ACE/RHESSI/WIND joint workshop in 2003 that led to the works of Emslie et al. (2004, 2005). These papers provided the first detailed analysis of most of the components of two well-observed SEEs, including the energies in thermal plasma, flare-accelerated electrons and ions, associated CME, and solar energetic particles (SEPs). Emslie et al. (2004) showed that the energy in the magnetic field was sufficient to power the thermal soft X-ray (SXR) emitting plasma, the flare-accelerated electrons and protons, and the kinetic energy in the CME, and they provided order-of-magnitude estimates of the partition of the energy amongst these components. Emslie et al. (2005) also considered the energy in the optical and EUV continua, and they cautioned that, due to the transfer of one energy component to another (e.g., flare-accelerated electrons $\rightarrow$ thermal plasma $\rightarrow$ SXR emission), care must be taken in summing energetic components to

arrive at the total energy released in an SEE. The present paper is also motivated by the work of Mewaldt et al. (2008a), which was the first to address the ratio of two energetic components (the CME energy in the rest frame of the solar wind and the energy in SEPs) for a statistically significant number of well-observed events.

The basic objective of the paper is to conduct a statistical study of the energy partition into different components for many of the larger SEEs observed during the previous maximum of solar activity, particularly during the period February 2002 through December 2006, the first five years of observations by the Ramaty High Energy Solar Spectroscopic Imager (*RHESSI*; Lin et al. 2002). The intent is to apply previously proven techniques to determining the global energetics of many more events than the two studied by Emslie et al. (2004, 2005), and, where possible, to apply new techniques to improve the energy estimates.

Our energy estimates come from a wide variety of observations: CME kinetic and potential energies from the Large Angle and Spectrometric COronagraph (LASCO; Brueckner et al. 1995) instrument on the Solar and Heliospheric Observatory (SoHO); energy in flare-accelerated charged particles from the hard X-rays and gamma-rays observed by *RHESSI*; energy contained in the SXR-emitting hot plasma from the Geostationary Operational Environmental Satellites (GOES) and *RHESSI*; energy in SEPs from the suite of instruments on the Advanced Composition Explorer (ACE) and from GOES, SoHO, the Solar Anomalous and Magnetospheric Particle EXplorer (SAMPEX), and the Solar TERrestrial RELations Observatory (STEREO); and total radiated energy from the Total Irradiance Monitor (TIM, Kopp & Lawrence 2005) on the Solar Radiation and Climate Experiment (SORCE). For weaker events, or where total irradiance measurements are not available, the Flare Irradiance Spectral Model (FISM; Chamberlin et al. 2007, 2008) was used to provide estimates of the bolometric output of a flare based on other measurements.

In Section 2 we present the events studied and review the techniques used to estimate the different component energies of each event. In Section 3 we present a series of scatter plots of one energy component against another. While the uncertainties on the different energy estimates are large (often an order of magnitude or greater), these scatter plots, because of the relatively large number of events they contain, nevertheless allow some general conclusions to be reached (Section 4) about how the energy is partitioned. The spread in the values for the different energy components also gives an idea of the uncertainties in the measured parameters and the range of flare intensities of the selected events. These plots also allow for the identification of a few “outlier” events (Section 5) that indicate either larger measurement uncertainties or distinctly different energy partitioning for those events. We summarize the results in Section 6, which also provides suggestions for future work.

2. Component Energies of the Solar Eruptive Events

The list of events studied includes the largest SEP events observed after February 2002, when *RHESSI* was launched. Additional events include all flares for which *RHESSI* detected significant emission in the 2.223 MeV neutron-capture gamma-ray line (Shih 2009; Shih et al. 2009). This, plus the inclusion of an intriguing behind-the-limb event with a strong CME on 2002 July 20 (Event #5 in Table 1), resulted in a total of 38 events for study. As permitted by the available data, estimates were made of the energies of the following components:

1. Radiated energy in the GOES 1 – 8 Å band;
2. Total radiated energy from the SXR-emitting plasma;
3. Total (bolometric) radiated output;
4. Peak thermal energy of the SXR-emitting plasma;
5. Energy in flare-accelerated electrons;
6. Energy in flare-accelerated ions;
7. CME kinetic energy in the rest frame of the Sun;
8. CME kinetic energy in the solar-wind rest frame;
9. CME gravitational potential energy;
10. Energy in SEPs; and
11. Free (nonpotential) magnetic energy in the active region

The data on these component energies are summarized in Table 1. GOES SXR data are available for all the events. However, because of missing or inadequate data or limited instrument sensitivities, definitive energy estimates for all the energy components listed above are available for only six events (Events #13, 14, 20, 23, 25, and 38). As mentioned above, Event #5 was located behind the limb; thus no magnetic energy estimate could be obtained and the associated radiated energies are listed as lower limits.

Table 1. Event List with Component Energies ($\times 10^{30}$ ergs)

No.	Date*	Time**	Class	SXR ¹	T-rad ²	Bol ³	Peak ⁴	Elec ⁵	Ion ⁶	KE ⁷	SW ⁸	PE ⁹	SEP ¹⁰	Mag ¹¹
1	02/02/20	05:52	M5.1	0.043	1.2	13	...	...	...	17	5.6	6.3	0.13	1200
2	02/04/21	00:43	X1.5	1.2	38	150	13	20	...	230	160	5.0	23	660
3	02/05/22	03:18	C5.0	0.048	5.6	9	...	...	...	84	45	10	2.7	260
4	02/07/15	19:59	X3.0	0.31	6.4	44	>2.2	>3.6	...	160	76	10	3.8	1500
5	02/07/20	21:04	X3.3 [†]	>1.5	>26	>210	...	...	...	260	170	...	...	...
6	02/07/23	00:18	X4.8	1.2	19	150	2.5	32	39	260	150	20	<30	2000
7	02/08/24	00:49	X3.1	1.1	24	160	5.9	11	...	210	130	16	3.9	2500
8	02/11/09	13:08	M4.6	0.11	5.0	8	1.3	60	...	180	110	20	0.51	550
9	03/05/27	22:56	X1.4	0.16	3.6	16	2.8	7.4	0.19	...	...	...	...	260
10	03/06/17	22:27	M6.9	0.21	4.6	17	2.4	4.6	6.7	...	...	...	...	140
11	03/10/26	17:21	X1.2	1.2	31	88	...	...	...	240	130	32	0.75	1700
12	03/10/28	09:51	X17	4.4	68	362 [‡]	>19	>56	>190	1200	850	63	43	2900
13	03/10/29	20:37	X10	1.9	31	137 [‡]	11	110	30	340	220	25	9.7	2900
14	03/11/02	17:03	X8.3	1.8	24	130	9.3	130	68	270	200	10	9.3	2800
15	03/11/03	09:43	X3.9	1.1	17	97	2.4	120	3.1	...	...	...	...	780
16	03/11/04	19:29	X28	4.8	72	426 [‡]	>3.1	>21	...	610	410	25	5.3	2800
17	04/07/15	18:15	X1.6	0.16	4.1	8	0.93	42	<0.1	...	...	...	...	820
18	04/07/25	05:39	M7.1	0.069	1.3	10	...	...	...	...	...	...	2.9	2300
19	04/11/07	15:42	X2.0	0.32	5.0	56	3.0	43	...	220	130	25	4.2	610
20	04/11/10	01:59	X2.5	0.32	7.7	15	2.0	20	3.4	230	180	16	2.4	610
21	05/01/15	00:22	X1.2	0.23	4.7	23	5.0	32	...	...	...	...	...	1500
22	05/01/15	22:25	X2.6	1.3	22	78	7.1	63	15	730	540	...	...	1600
23	05/01/17	06:59	X3.8	1.8	34	150	17	48	13	1000	730	50	11	1600
24	05/01/19	08:03	X1.3	0.43	7.0	54	5.9	82	29	...	...	...	...	1600
25	05/01/20	06:36	X7.1	2.9	43	150	10	25	120	15 - 79	7.8 - 61	2.0	7.8	1600
26	05/05/13	16:13	M8.0	0.44	14	49	3.1	13	...	39	22	4.0	7.3	400
27	05/07/14	10:16	X1.2	0.64	12	87	4.3	24	...	100	66	6.3	2.9	310
28	05/07/27	04:33	M3.7	0.16	4.5	30	1.3	12	...	100	62	10	...	310
29	05/08/22	16:46	M5.6	0.34	9.8	35	3.2	6.3	...	110	76	10	6.4	390
30	05/08/25	04:31	M6.4	0.050	1.2	11	1.1	16	<1.9	...	...	...	...	110
31	05/09/07	17:17	X17	4.9	68	322 [‡]	>5.6	>10	>0.7	...	...	...	...	1400
32	05/09/09	19:13	X6.2	3.1	44	250	>7.9	>120	>1.7	...	...	...	...	1300
33	05/09/10	21:30	X2.1	0.99	17	82	6.0	13	1.0	...	...	...	...	1300
34	05/09/13	19:19	X1.5	1.1	25	85	...	...	...	330	200	32	3.0	1400
35	05/09/13	23:15	X1.7	0.23	4.7	21	2.3	32	<0.1	...	...	...	...	1400
36	06/12/05	10:18	X9.0	1.4	19	92	>5.1	>360	>4.5	...	...	...	...	400
37	06/12/06	18:29	X6.5	1.1	18	59 [‡]	6.8	40	36	...	...	...	...	410
38	06/12/13	02:14	X3.0	1.1	17	75	4.8	13	14	74	44	6.3	3.2	570

*In yy/mm/dd format. ** (UT).

¹Radiated energy in the GOES 1 – 8 Å band. ²Total radiated energy from the SXR-emitting plasma.

³Bolometric radiated energy. ⁴Peak thermal energy of the SXR-emitting plasma.

⁵Energy in flare-accelerated electrons. ⁶Energy in flare-accelerated ions.

⁷CME kinetic energy in the rest frame of the Sun. ⁸CME kinetic energy in solar-wind rest frame.

⁹CME gravitational potential energy. ¹⁰Energy in SEPs. ¹¹Nonpotential magnetic energy in the active region.

[†]Behind-the-limb event. [‡]Bolometric irradiance directly measured with TIM – see Table 2.

2.1. Radiated Energy from Hot Plasma

For each event, we estimated the time-integrated SXR and total radiated energies from the hot SXR-emitting plasma – the columns labeled ‘SXR’ and ‘T-rad’, respectively, in Table 1. Fluxes in W m^{-2} for the 1–8 Å and 0.5–4 Å bands are provided by one of NOAA GOES satellites every 3 s. The total emission in the 1–8 Å band (‘SXR’) is obtained simply by summing the background-subtracted fluxes over the duration of the flare, from the GOES start time (given by NOAA and listed in Table 1) to the time when the flux had decreased to 10% of the peak value. The background that was subtracted was taken as the lowest flux in the hour or so before and/or after the flare.

To calculate the radiated energy from the hot plasma, we used the measured GOES SXR fluxes in a manner similar to that described in Emslie et al. (2004), specifically using the IDL GOES Workbench available in SolarSoftware (SSW). This allows us to obtain a consistent set of values for all events since GOES, unlike *RHESSI*, has full coverage for all events. This calculation assumes that the hot plasma at any given time is isothermal; the temperature and emission measure are calculated from the two-channel GOES data using the relations given by White et al. (2005). Using the thus-inferred emission measure and temperature, and the optically thin radiation loss rate vs. temperature function (for coronal abundances and Mazzotta et al. (1998) ionization equilibria) taken from the CHIANTI database (Dere et al. 1997, 2009), we used the IDL procedure *rad_loss*, available in SSW, to calculate, for each 3-s time interval, the energy radiated from the SXR-emitting plasma over all wavelengths. Finally, we summed the radiated energies over the duration of the flare to produce the total radiated energy given in the column labeled ‘T-rad’ in Table 1.

2.2. Bolometric Irradiance

Estimates of the bolometric irradiance, the total energy radiated from the flare integrated across the entire solar spectrum, for each of the events are provided in the column labeled ‘Bol’ in Table 1. For five of the events listed in Table 1, the bolometric irradiance was measured directly by the Total Irradiance Monitor (TIM, Kopp & Lawrence 2005) onboard SORCE as an increase in the total solar irradiance above the (highly variable) pre- and post flare background levels. Total flare irradiance values were reported in this manner for Events # 12, 13, 16, and 31 by Woods et al. (2006), and the bolometric irradiance for event #37 will be reported by Moore et al. (2012, in preparation). Both previously published values and revised estimates made for this paper are listed in Table 2. A final correction factor (see Table 2) was then applied to allow for limb-darkening absorption when the path to the observer becomes optically thick at some wavelengths; the value of this factor can be up to

~ 3.0 – see Equation (2) in Woods et al. (2006).

To complement these direct measurements and so provide a consistent set of bolometric values for all of the events in Table 1, estimates from the Flare Irradiance Spectral Model (FISM; Chamberlin et al. 2007, 2008) were used, with various assumptions and corrections as described below. FISM is an empirical model that provides estimates of the total amount of solar radiated energy over a broad wavelength range from 1–1900 Å and over a wide range of time scales from seconds to years. It uses measurements in this wavelength range from the Solar EUV Experiment (SEE; Woods et al. 2005) on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite and the SOLar-STellar Irradiance Comparison Experiment (SOLSTICE; Rottman et al. 1993) on the Upper Atmosphere Research Satellite (UARS).

For the relatively rapid GOES 1 – 8 Å SXR flux variations that occur during a solar flare, different empirical factors appropriate to the rise and decay phases of the flare, respectively, are used to relate the SXR flux to the total radiated energy during those phases. Various daily proxies are also used to represent the more gradual variations in solar irradiance due to active region evolution, solar rotation, and the solar cycle. The daily pre-flare irradiance spectrum is subtracted from each value to get the radiated energy from the flare alone, and this is then integrated over the duration of the GOES flare to get the total radiated energy in erg cm^{-2} at the detector. Then, assuming uniform radiation over 2π steradians, the total radiated energy from the flare in the 1–1900Å wavelength range can be calculated, with 1-minute cadence.

The 1–1900Å solar irradiance is converted to total radiated energy over all wavelengths (the bolometric irradiance) by multiplying by an empirical conversion factor of 2.42 ± 0.31 , determined by comparing the 1–1900Å solar irradiance with the absolute bolometric intensity for the five flares for which the latter could be measured directly (see Table 2).

The uncertainties on the calculated values of the bolometric irradiance listed in Tables 1 and 2 are made up of several parts. The most dominant uncertainty comes from the TIM measurements themselves, and is due to the variations in the total solar irradiance of the non-flaring Sun. Other contributions to the overall uncertainty are the errors on the FISM estimates of the 1–1900 Å flux, the conversion from UV irradiance to total solar irradiance, and the limb-darkening correction. The overall uncertainty on the calculated values is $\pm \sim 70\%$ for those events that are near disk center and $\pm \sim 90\%$ for the near limb events.¹

¹Because the conversion of the FISM radiated energy to bolometric energy is based on the five events measured directly with TIM, the bolometric energies for these five events derived from the FISM estimate differ (after correcting for limb darkening) by less than 40% from the directly measured values.

2.3. Peak Thermal Energy Content of the Hot Plasma

The peak thermal energy content of the SXR-emitting plasma (the column labeled ‘Peak’ in Table 1) was determined from *RHESSI* images and spectra. (GOES data alone cannot be used since, in addition to the emission measure and temperature, a volume estimate is required, and that can only be obtained from *RHESSI* images. Thus, we have incomplete coverage of this parameter depending on the timing of each event in *RHESSI*’s day/night cycle.) We first fit the observed *RHESSI* hard X-ray spectrum with the sum of a single-temperature Maxwellian plus the form expected from a double-power-law electron spectrum (Equation 2 in Section 2.4). The fit parameters appropriate to both thermal and nonthermal components were determined using the forward-fitting method implemented in the OSPEX software package available in SSW. The temperatures and emission measures obtained from *RHESSI* in this way tend to agree closely with the corresponding values obtained from the standard GOES data analysis discussed in Section 2.1, although higher temperatures can be obtained because of the *RHESSI* coverage to higher energies. Indeed, superhot components with reported temperatures as high as ~ 50 MK may exist in some flares and are not accurately reflected in the GOES thermal analysis (Lin et al. 1981; Caspi 2010; Caspi & Lin 2010). The thermal function included the line plus continuum components determined using CHIANTI, again with coronal abundances and Mazzotta et al. (1998) ionization equilibria. From these fits, the average temperature T_0 (K) and emission measure $EM = \int n_e^2 dV$ (cm^{-3}) of the thermal plasma were determined every 20 s throughout the flare. (Here n_e is the electron density (cm^{-3}) and V is the emitting volume (cm^3).)

Next, *RHESSI* Clean images made using the 3σ -clean method described by Dennis & Pernak (2009) were used to provide estimates of the apparent source volume (V_{ap}), as described in Emslie et al. (2004). The thermal energy content of the plasma was then calculated from the expression (e.g, de Jager et al. 1986)

$$U_{\text{th}} = 3 n_e k T_0 f V_{\text{ap}} \simeq 4.14 \times 10^{-16} T_0 \sqrt{EM \times f V_{\text{ap}}} \text{ erg}, \quad (1)$$

where k is Boltzmann’s constant and f is the volumetric filling factor, assumed here to be unity. The peak energy values listed in Table 1 are the highest values of U_{th} obtained from this analysis, usually at or near the time of the peak GOES flux.

2.4. Flare-Accelerated Electrons

The energies in flare-accelerated electrons are listed in the column labeled ‘Elec’ in Table 1. They were determined by using the OSPEX algorithm to fit a combined isothermal-plus-nonthermal function to the measured *RHESSI* spatially integrated X-ray spectra. The

nonthermal component was assumed to be bremsstrahlung from energetic electrons with an injected spectrum $F_0(E_0)$ (electrons $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$) in the form of a broken power-law:

$$F_0(E_0) = A \begin{cases} 0 & , E_0 < E_{\min} \\ (E_0/E_p)^{-\delta_1} & , E_{\min} \leq E_0 < E_b \\ (E_0/E_p)^{-\delta_2} (E_b/E_p)^{\delta_2-\delta_1} & , E_b \leq E_0 < E_{\max} \\ 0 & , E_{\max} \leq E_0 \end{cases} . \quad (2)$$

The seven parameters of this model spectrum are the normalization parameter, A , the low and high energy cutoffs, $E_{\min}$ and $E_{\max}$, the break energy E_b , and the power-law indices δ_1 and δ_2 below and above the break energy, respectively. The (arbitrary) value of the pivot energy E_p was fixed at 50 keV. Also, the high energy cutoff $E_{\max}$ was fixed at 30 MeV, an energy so high above the energy range of interest ($\lesssim 500$ keV) that it has a negligible effect on the calculated X-ray spectrum and so is equivalent to having no high-energy cutoff at all.

The OSPEX analysis uses a forward-fitting procedure that starts by dividing the flare into multiple time intervals – here we used 20 s intervals. For each interval, the function *thick2* in SSW is used with a set of starting parameters for the electron spectrum (2) used to calculate the X-ray photon spectrum assuming a target that is “cold,” in the sense that the ambient electrons have a mean energy kT that is significantly lower than the lowest energy of the accelerated electrons. In general, consideration must also be given to the ionization state of the target, since the bremsstrahlung efficiency is a factor of ~ 3 times higher for a fully-ionized plasma than for an un-ionized gas (Brown 1973). However, since most of the beam energy is in the lower energy electrons that stop higher in the corona, we used parameters appropriate for a fully-ionized plasma to calculate the total nonthermal energy. A more refined calculation is possible using the procedure outlined by Kontar et al. (2002) and Su et al. (2011), but no significant difference is expected in the resulting total energy in electrons above $E_{\min}$.

The resulting photon spectrum is then folded through the detector response matrix to generate a count-rate spectrum. This is added to the count-rate spectrum calculated for the thermal spectrum discussed in Section 2.1. Finally, through an iterative procedure, we find best-fit values of the parameters describing the electron spectrum (2), by minimizing the χ^2 statistic between the calculated and the measured background-subtracted count rates. The total energy in electrons for a given event as listed in the column labeled ‘Elec’ in Table 1 is then computed by integrating the best-fit electron energy spectrum above $E_{\min}$ for each time interval and summing the results over the duration of the flare.

In order to obtain the most reliable spectral fits to the *RHESSI* data and thus better evaluate the uncertainties in the calculated values of U_e , we chose to use data from just one of *RHESSI*’s nine detectors – Detector #4. This particular detector has good energy reso-

lution and sensitivity, which allowed us to apply the most up-to-date corrections for energy resolution and calibration, photospheric albedo, pulse pile-up, and background subtraction that are available with the current analysis software. For the large events studied, the count rates were sufficiently high that selecting just a single detector did not seriously degrade the spectroscopic capability up to the photon energies required to determine the parameters of interest. Milligan & Dennis (2009) have shown that similar best-fit parameter values are determined using different individual detectors (detectors 1, 3, 4, 5, 6, and 9 in their case), which leads to an estimate of the systematic uncertainties in the calculated total energy in electrons of $\sim 20\%$. This is negligible compared to the uncertainty arising from the difficulty in establishing the value of the low energy cutoff energy $E_{\min}$, an uncertainty that arises because the thermal emission generally dominates the low-energy part of the X-ray photon spectrum up to energies where the effects of a cutoff in the electron spectrum might be detectable. We used the largest value of $E_{\min}$ that still gave an acceptable fit (reduced $\chi^2 \simeq 1$). As a result, the values of U_e listed in Table 1 are lower limits to the energy in the nonthermal electrons. Furthermore, because of the steep form of the electron spectra ($\delta_1 \gtrsim 4$), these values are particularly sensitive to $E_{\min}$, so that the energies in flare-accelerated electrons could be up to an order of magnitude higher than those reported in Table 1.

2.5. Flare-Accelerated Ions

The energies in flare-accelerated ions with energies above 1 MeV are listed in the column labeled ‘Ion’ in Table 1. In order to provide a consistent set of values for as many events as possible, the energies were estimated solely from *RHESSI* measurements of the fluence (time-integral of the flux, photons cm^{-2}) in the 2.223 MeV neutron-capture gamma-ray line. Consequently, energies are included only for those flares with $>4\sigma$ detections of that line, as reported by Shih (2009) and Shih et al. (2009), plus three additional flares that occurred in 2006 (Events #36, 37 and 38). We chose a lower energy threshold of 1 MeV because the production of detected nuclear gamma-ray lines from elements such as ^{20}Ne begins at energies as low as ~ 3 MeV, and it is therefore evident that the ion spectrum extends down to ~ 1 MeV, at least in a few large events (Ramaty et al. 1995; Ramaty & Mandzhavidze 2000). The spectral shape is essentially unknown below 1 MeV.

In order to estimate the energy in ions from the 2.223 MeV line fluences, the following steps were taken. The measured fluences of the line were first corrected for attenuation in the solar atmosphere assuming a given depth of production of the photons (Hua & Lingenfelter 1987) and allowing for the flare position on the solar disk. The corrected fluence values were then converted to the proton energy above 30 MeV using conversion factors given by

Murphy et al. (2007) and Shih (2009). The 30 MeV threshold was used at this stage in the analysis because the 2.223 MeV line is produced by ions with energies $\gtrsim 20$ MeV nucleon⁻¹, so that the conversion factors are less dependent on the assumed power-law index of the proton spectrum.

In order to estimate the energy in protons above 1 MeV, an extrapolation is required over one-and-a-half orders of magnitude in proton energy, so that the inferred energy above 1 MeV depends critically on the spectral index used in this extrapolation. For the largest *RHESSI* flares, where multiple types of ion-associated gamma-ray emission can be detected and fit simultaneously, the ion power-law spectral indices are found to be typically in the range 3–5, a range of indices consistent with that found in a study of flares observed by the Gamma-Ray Spectrometer on the Solar Maximum Mission (Ramaty et al. 1996). Consequently, for the purposes of estimating the total energy in protons, we have assumed a power-law proton spectrum with a single spectral index of 4 that extends down to a lower cutoff energy of 1 MeV. Because of the long “lever arm” associated with this extrapolation, an uncertainty in the spectral index of ± 1 corresponds to an uncertainty in the total energy content above 1 MeV of about ± 1.5 orders of magnitude.

Even under the assumption that the spectra for the various types of ions have the same spectral index and low-energy cutoff, the energy content will also depend on the accelerated particle composition. The ratio of the energy content in all ions (protons plus α -particles and heavier nuclei) to the energy in protons can vary between ~ 2 and ~ 6 ; here we assume that the energy in flare-accelerated ions is three times the energy content in flare-accelerated protons.

For a number of the events, the total energy content of ions listed in Table 1 is a lower limit because *RHESSI* did not see the complete time history as the result of spacecraft night or passage through the South Atlantic Anomaly (SAA). In addition, there can be other complications that affect the observation or interpretation of the neutron-capture line. The affected events are as follows:

- Event #12: *RHESSI* missed a significant fraction of the neutron-capture line emission, including the peak, as shown by observations of this flare by *INTEGRAL* (Kiener et al. 2006);
- Event #31: *RHESSI* observed only ~ 2 minutes of a significantly longer impulsive phase. Furthermore, the level of atmospheric attenuation is very uncertain due to this flare’s large heliocentric angle, so we use a conservative angle of 80° to determine the correction factor;

- Events #32 and 37: *RHESSI* missed the peak of the impulsive emission, and thus possibly a significant fraction of the total emission;
- Event #36: *RHESSI* missed some fraction of the 2.223 MeV emission as it was just coming out of Earth shadow. *RHESSI* observations started at 10:31 UT and the GOES X-ray flare started at $\sim 10:19$ UT;
- Events #14, 15, 22, 33, and 38: *RHESSI* likely missed a small fraction of the neutron-capture line emission late in the flare. However, this missing energy is smaller than the other uncertainties in the energy estimates discussed above;
- Events #36, 37, and 38: By December 2006, *RHESSI*'s detectors had reduced gamma-ray sensitivity resulting from accumulated radiation damage, a reduction that is difficult to estimate.

2.6. Coronal Mass Ejection

The CME kinetic energies, both in the rest frame of the Sun and in that of the solar wind (for comparison with the SEP energies - see Section 3.6), are listed in the columns labeled ‘KE’ and ‘SW,’ respectively, of Table 1. The gravitational potential energies of the CMEs are listed in the column labeled ‘PE.’ These CME energies were estimated from calibrated LASCO images using the procedure detailed in Vourlidas et al. (2010, 2011).

Briefly, this procedure consists of the following steps. First, we selected two LASCO images, one containing the CME and the other taken before the event as close in time as possible to the flare with no disturbances or ejecta over the path of the subsequent CME. Next, the images were calibrated (in units of mean solar brightness) and the pre-event image was subtracted from the CME image. The excess brightness revealed by this subtracted image is due to Thompson scattering of photospheric radiation from the excess mass in the CME. This excess brightness can therefore be converted to excess mass of the CME under the usual assumptions that (1) all of the CME mass is concentrated on the plane of the sky, and (2) the CME material consists of 90% H and 10% He (Poland et al. 1981; Vourlidas et al. 2000, 2010). We used the first assumption because the true three-dimensional distribution of the CME mass along the line of sight is unknown. The second assumption represents an “average” coronal composition, since we do not know the height at which the bulk of the CME material originates (other than that it is coronal).

These assumptions together result in a lower limit for the mass. The uncertainty in the CME mass becomes more significant as the central angle and/or spread of a given CME

departs significantly from the plane of the sky. The mass underestimation is about a factor of 2 for CMEs that are $\lesssim 40^\circ$ from the sky plane (Vourlidas et al. 2010).

Other uncertainties in this procedure include exposure time variations between event and pre-event images, improper vignetting correction, solar rotation effects, and the presence of stars in the field of view. Fortunately, such uncertainties can be minimized to a level that is well below that of other factors through proper calibration and careful choice of event and pre-event images.

After obtaining a series of excess masses of the CME as a function of time, we can compute both the total mass of the CME and the position and projected velocity, both for the leading edge and for the center of mass of the CME. From the mass, position, and velocity we can straightforwardly estimate the total kinetic (U_K) and potential (U_Φ) energies. These values are again lower bounds since both the mass and the speed are projected quantities. Vourlidas et al. (2010) estimate that, for CMEs that are far away from the sky plane and that have relatively small widths, the kinetic energy could be as much as a factor of eight times larger than the values derived above; similarly the potential energy could be as much as twice as large for such events. However, for the majority of events, the uncertainties on the quoted energies are within a factor of two. To obtain the kinetic energy in the solar wind rest frame (as an estimate of the energy available for shock acceleration of SEPs), we simply subtracted 400 km s^{-1} from the measured CME speed and recomputed the kinetic energy (see Section 3.6).

2.7. Solar Energetic Particles (SEPs)

For the majority of the events studied, it is likely that the interplanetary SEPs in the events studied are accelerated by CME-driven shocks. (A possible exception is the 2002 February 20 event, where particles directly accelerated in the flare could dominate; see Chollet et al. 2010). The energy content of the accelerated SEPs, particularly when compared to the kinetic energy of the CME in the solar wind rest frame, is therefore an important measure of the efficiency of SEP production by the CME.

The energy content of SEPs that escape into interplanetary space has been estimated by measuring the energy spectra of electrons from ~ 0.035 to $\sim 8 \text{ MeV}$, protons from ~ 0.05 to $\sim 400 \text{ MeV nucleon}^{-1}$, and abundant heavier ions from ~ 0.05 to $\sim 100 \text{ MeV nucleon}^{-1}$. Estimates were made in a number of large events from Solar Cycle 23 using a combination of nine separate instruments. The proton spectra are based on data from the Ultra-Low Energy Isotope Spectrometer (ULEIS; Mason et al. 1998), and the Electron, Proton, and Alpha

Monitor (EPAM; Gold et al. 1998) on ACE; from the Proton/Electron Telescope (PET; Cook et al. 1993) on SAMPEX; and from the Energetic Particle Sensors (EPS; Onsager et al. 1996) on NOAA’s GOES-8 and GOES-11 satellites. Spectra of helium and heavier ions were measured by the Solar Isotope Spectrometer (SIS; Stone et al. 1998) on ACE and by ULEIS. Also used for the 2006 events were two STEREO instruments, the Low Energy Telescope (LET; Mewaldt et al. 2008b) and High Energy Telescope (HET; von Rosenvinge et al. 2008). Electron measurements were provided by ACE/EPAM, SAMPEX/PET, and by the Electron Proton Helium INstrument (EPHIN; Müller-Mellin et al. 1995) instrument on SoHO.

For eleven of these events, the energy spectra of H, He, and abundant heavier ions were all fit with common spectral forms that include the double-power-law function of Band et al. (1993) and the Ellison-Ramaty spectrum – a power-law with an exponential cutoff. Examples of energy spectra and both functional forms are given in Mewaldt et al. (2005, 2012) and Cohen et al. (2005). For the remainder of the events, the proton energy spectra were fit and the contributions of He and heavier ions were estimated using element abundances measured for these events by ULEIS and SIS. The electron contribution was measured in each of the individual events using either EPAM and PET, or EPAM and EPHIN.

For all of the fluence measurements described above, the instruments were located near-Earth. As in Emslie et al. (2004), we used the measured near-Earth fluence spectra, typically integrated over 3 to 5 days, to estimate the energy cm^{-2} that escaped beyond 1 AU in the form of SEPs. To obtain this estimate, Emslie et al. (2004) corrected for the fact that SEPs can scatter back and forth across 1 AU (providing multiple opportunities to be measured) using correction factors based on simulations by Giacalone (personal communication, 2002). A similar approach was followed in analyzing the “Halloween” events (Mewaldt et al. 2005) and in a subsequent survey of 17 events (Mewaldt 2006). Mewaldt et al. (2008a) improved on these estimates in a study of 23 SEP events from 1997-2005 by correcting for the fact that SEPs also lose energy as they scatter on the diverging interplanetary magnetic field (IMF).

For this work, we corrected for both multiple 1-AU crossings and energy loss using new simulations by Chollet et al. (2010) for four species (H, He, O, and Fe) with a range of charge-to-mass ratios. They considered scattering mean free paths ranging from $\lambda = 0.01$ to 1 AU, and also varied the radial and rigidity dependence of λ . Surprisingly, the source energy required to account for the accelerated particles in these different scattering descriptions varied by less than a factor of ~ 2 . This is apparently because the scattering and energy-loss processes compensate for each other – the more particles scatter the more often they cross 1 AU, but they also lose more energy in the process. In this paper we have used their form of λ derived from quasi-linear theory (see Equation (3) in Chollet et al. 2010).

To relate the measured near-Earth values of MeV cm^{-2} to the integrated contribution of SEPs escaping through a 1-AU sphere surrounding the Sun, we need to know how SEPs from a given source location are distributed in longitude and latitude. Emslie et al. (2004) found that the largest SEP events measured by GOES and ACE originated near central meridian; for CMEs launched from other locations, they assumed that the SEP fluence at Earth falls off exponentially with e-folding separations of 35° for latitude, 45° for western events, and 25° for eastern events. Since then, Lario et al. (2006) have measured the longitudinal distribution of SEPs using two- and three-spacecraft data from the two Helios spacecraft and the Interplanetary Monitoring Platform-8 (IMP-8). They adopted a Gaussian spatial distribution given by $F = F_o \exp[-(\Phi - \Phi_0)^2/2\sigma^2]$, where Φ is the longitude of the observer, Φ_0 is located 25.8° east of the point of best solar wind connection for a 450 km s^{-1} solar wind ($\sim \text{W}52^\circ$), and $\sigma = 38^\circ$. We use their result for the fluence of 4 - 13 MeV protons, and assume it also applies to latitude differences. By using this relation with the measured flare location and the near-Earth value for the escaping MeV cm^{-2} , we obtained the source energy required to supply SEPs escaping over a 1-AU sphere centered on the Sun. The results are tabulated in the ‘SEP’ column of Table 1. The typical upper and lower bound uncertainties in the SEP energies are conservatively estimated to be +200% and -67%, respectively.

2.8. Nonpotential Energy in the Active Region Magnetic Field

It is commonly believed that the fundamental energy source for an SEE lies in current-carrying magnetic fields. In such a scenario, the free energy available to power the event is the excess “non-potential” magnetic energy – the energy above the minimum-energy, potential (i.e., current-free) field to which the field can relax. The estimated available nonpotential magnetic energies of the active region producing the SEEs are listed in the column labeled ‘Mag’ of Table 1. The estimates were made from full-disk line-of-sight (LOS) magnetograms obtained from the Michelson Doppler Imager (MDI; Scherrer et al. 1995) on SoHO, using the method described by Welsch et al. (2009) and outlined below.

Numerous efforts have been undertaken to estimate nonpotential magnetic energies in active regions near disk center. The methods include: (1) using the magnetic virial theorem estimates from chromospheric vector magnetograms (Metcalf et al. 1995, 2005); (2) semi-empirical flux-rope modeling using $\text{H}\alpha$ and EUV images with MDI line-of-sight (LOS) magnetograms (Bobra et al. 2008); and (3) MHD modeling (Metcalf et al. 1995; Jiao et al. 1997) and non-potential field extrapolation based upon photospheric vector magnetograms (Guo et al. 2008; Schrijver et al. 2008; Thalmann & Wiegmann 2008; Thalmann et al. 2008). These methods are labor intensive, and uncertainties in their energy estimates are large. For

example, error bars on virial free energy estimates can exceed the potential magnetic energy. Also, there is considerable scatter in estimates from studies that employ several methods to analyze the same data (e.g., Schrijver et al. 2008). A couple of generalizations, however, can be made. Free energies determined by virial methods matched or exceeded the potential field energy, while free energies estimated using other techniques typically amounted to a few tens of percent of the potential field energy. Published values for free energies in analytic (Schrijver et al. 2006) and semi-empirical (Metcalf et al. 2008) fields meant to model solar fields also hover around a few tens of percent of the potential field energy.

We estimated the free (i.e., nonpotential) magnetic energies listed in Table 1 to be 30% of the potential magnetic energy determined from MDI full-disk LOS magnetograms. This is believed to be a conservative estimate but it has the advantage that it can be readily determined for most of the events. Some of the events arose from limb active regions, for which simultaneous magnetograms are unavailable. Even if vector magnetograms were available, uncertainties in free energies would still be large. With published virial free energy estimates ranging to a few times the potential energy, it is possible that the true free energy could exceed our estimates by a factor of ~ 10 .

Apart from two cases where flux was clearly emerging near the time of the event (Events #29 and #38), we calculated the potential magnetic energies from magnetograms in which each event’s source active region was near the disk’s central meridian, assuming a rigid rotation rate of $13^\circ \text{ day}^{-1}$. This means the energy estimates were sometimes made a few days before or after a given event. Fields were assumed to be radial, so each pixel’s line-of-sight field strength B_{LOS} was divided by the cosine of the heliocentric angle between the pixel and the sub-observation point, to generate an estimated radial field, B_R . Using a Mercator projection (Welsch et al. 2009), the corrected pixel values were then interpolated onto a 2-D plane. Next, the scalar potential χ , where $\mathbf{B} = -\nabla\chi$, was determined using a Green’s function method. Finally, the magnetic energy U_M was estimated by integrating $(\chi B_R/8\pi)$ over manually-defined cropping windows that contained each active region. Images of the magnetograms used, as well as deprojected data with cropping windows, are online at <http://solarmuri.ssl.berkeley.edu/~welsch/public/meetings/SADOSC24/>.

In several cases in Table 1 (e.g., Events #22 to 25), the same value of the magnetic energy is given for adjacent events up to five days apart from the same active region. This is because the magnetic energy was estimated from line-of-sight magnetograms taken when the active region was close to disk center. These estimates become increasingly unreliable as the active region moves away from disk center. Thus, although it is very likely that the active region’s magnetic fields evolved substantially over the time between events, there is no way to reliably quantify these changes from the available magnetograms. This problem

will be alleviated with the now regularly available vector magnetic field measurements from the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) on the Solar Dynamics Observatory (SDO), which can be used to estimate the energy in regions located away from disk center.

3. Comparisons of Energetic Components

In this section we present comparisons of the energy contents of the various components discussed above, through a series of figures each showing logarithmic scatter plots (the “forest”) of the energy content of one component versus the energy content of another, for all events (the “trees”) for which data are available for both selected components. The scatter of the points around the logarithmic centroid is due both to the true range of energies of the selected events and to the often large uncertainties (up to 2.5 orders or magnitude in some cases) in the energy estimates of each component. If the uncertainties are random, then the centroid location gives an indication of the average ratio of the energies of the two components being plotted, and the scatter of the points about the centroid provides a measure of the overall uncertainty in that ratio. Any “outlier” point indicates an anomalous event, either because of intrinsic differences in the distribution of energies between the different components for such an event or because of some error in the energy estimates for that event.

The component energy comparisons are discussed in the following subsections, with associated plots given in Figures 1 to 3. In each plot, all events that have measured energies for both components are shown, with each point labeled by the corresponding event number in Table 1. (Note that events with only upper or lower limits are not shown, except for Events #5 and #25.) The logarithmic centroid is shown by a bullseye with its X and Y coordinates, calculated using Equation (A1), given in the upper left corner of the plot. The three diagonal dotted lines are lines of constant ratio R as defined by Equation (A2), with $R = Y/X = 100\%$, 10% and 1% . These lines each have tick marks showing the overall “size” of the event $A = \sqrt{XY}$ – see Equation (A3). The dashed-line ellipse shows the $\pm 2\sigma$ locus; the width of this ellipse perpendicular (Equation (A4)) and parallel (Equation (A5)) to the lines of constant ratio is a measure of the 2σ spread in the energy ratio, R , and the event size, A , respectively. Points outside this ellipse are considered as “outliers” and will be discussed in Section 5.

Table 3 lists, for each plot, the energetic components involved, the value of the logarithmic centroid energies and their ratio, the root-mean-square (RMS – 1σ) spreads in the values of the ratio R and the size A . Also, to quantify possible trends of one parameter vs. the

other, Table 3 lists the Spearman’s rank correlation coefficient ρ , a quantity that measures the correlation between their rank orders (lowest $\rightarrow$ highest) of the variables. The equations used to determine these different parameters are given in Appendix A.

3.1. Radiated Energy in the GOES 1 – 8 Å Band vs. Radiated Energy from SXR-emitting Plasma

Figure 1a shows the scatter plot for the radiated energy in the GOES 1 – 8 Å band vs. the total energy radiated from the hot SXR-emitting plasma. The points are closely rank-correlated ($\rho = 0.96$) and also cluster very closely in the perpendicular (R) direction, showing that the energy radiated in the GOES 1 – 8 Å band is a relatively constant fraction ($R = 0.05$) of the total energy radiated from the SXR-emitting plasma. Indeed, a regression analysis of the data in Table 1 shows that the ratio (best estimate $\pm 1\sigma$) of the total energy radiated by SXR-emitting thermal plasma in the flare to the observed GOES 1 – 8 Å flux is 15.4 ± 0.8 . This strong correlation is not surprising since both plotted energy components are calculated from the GOES SXR fluxes; the scatter about the trend line arises from the differences in the temperatures of the different events.

3.2. Thermal Radiated Energy vs. Peak Thermal Energy

Figure 1b shows the scatter plot of the total energy radiated from hot SXR-emitting plasma vs. the peak thermal energy content of that plasma. The relatively tight correlation ($\rho = 0.82$) between these two components is expected, since both parameters refer to the same SXR-emitting plasma. Event #30 (the M6.4 event on 2005 August 25) is the most extreme outlier but it is almost equally weak in both energy components. On average, the total energy radiated exceeds the peak thermal energy content by a factor of ~ 3 ($R = 2.7$ in Table 3), implying continuous re-energization of the SXR-emitting material as the flare progresses.

3.3. Peak Thermal Energy vs. Energy in Flare-Accelerated Nonthermal Particles

Figure 1c shows the scatter plot for the peak thermal energy in the hot SXR-emitting plasma vs. the energy in flare-accelerated nonthermal particles (electrons plus ions, when available). There is substantially greater spread in the points compared to Figure 1b, but

Table 2. TIM and FISM Bolometric Energies (10^{30} ergs)

Event No.	Date	TIM				FISM Corrected ²	Difference (TIM – FISM)/TIM
		Total ¹	Uncertainty ¹	Revised estimate	Corrected ²		
12	28-Oct-2003	600	39%	362	362	310	14%
13	29-Oct-2003	240	86%	137	137	128	7%
16	4-Nov-2003	260	65%	142	426	447	-5%
31	7-Sep-2005	300	71%	150	322	266	17%
37	6-Dec-2006	...	...	46 ³	59	82	-39%

¹Woods et al. (2006)

²Corrected for limb darkening

³Moore et al. (2012, in preparation)

Table 3. Parameters represented in scatter plots.

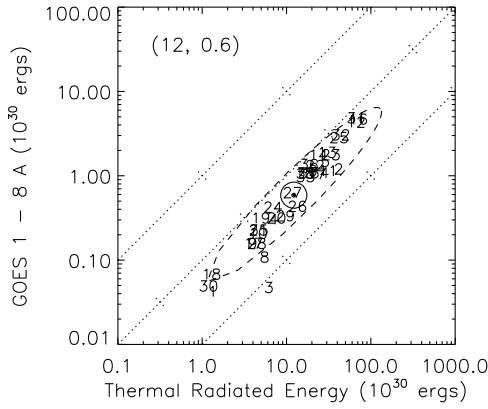
Figure No.	X-axis	Plotted Components Y-axis	Logarithmic Centroid*		R^{**}	RMS [†]		$\rho^{\ddagger}$
			$X_{centroid}$ (10^{30} ergs)	$Y_{centroid}$ (10^{30} ergs)		R	A	
1a	Radiated from Hot Plasma	GOES 1–8 Å	12	0.6	0.05	0.17	0.51	0.96
1b	Peak Thermal Energy	Radiated from Hot Plasma	3.9	11	2.7	0.22	0.34	0.82
1c	Electrons+Ions	Peak Thermal Energy	34	3.9	0.11	0.43	0.31	0.36
1d	Electrons+Ions	Radiated from Hot Plasma	34	11	0.31	0.43	0.34	0.46
2a	Electrons	Ions	32	11	0.34	0.63	0.52	0.45
2b	CME KE (SW frame)	SEP	110	4.0	0.04	0.49	0.47	0.47
2c	Ions	SEP	23	6.2	0.27	0.38	0.35	0.20
2d	Magnetic	Bolometric	890	55	0.06	0.43	0.38	0.56
3a	Magnetic	CME KE+PE (Sun frame)	1000	200	0.19	0.39	0.34	0.68
3b	CME KE+PE (Sun frame)	Bolometric	200	71	0.35	0.43	0.38	0.54
3c	Bolometric	Electrons+Ions	49	34	0.71	0.47	0.35	0.37
3d	Bolometric	Radiated from Hot Plasma	57	12	0.21	0.21	0.47	0.92

* X and Y values of the logarithmic centroid, computed using Equation (A1).

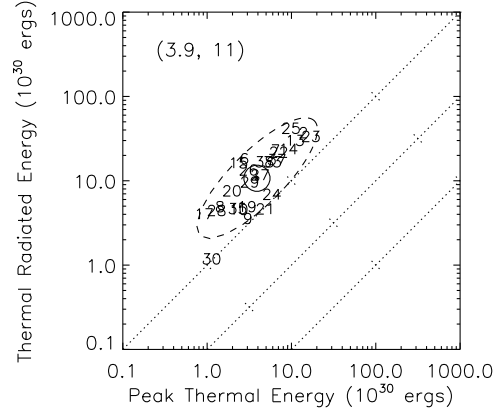
** $R = Y_{centroid}/X_{centroid}$, the ratio of Y and X values of the logarithmic centroid computed using Equation (A2).

† RMS (root mean square) values of $R = Y/X$ and $A = \sqrt{XY}$, computed using Equations (A4) and (A5). The RMS values of R and A , respectively, quantify the scatter perpendicular and parallel to the line of constant energy ratio that passes through the logarithmic centroid.

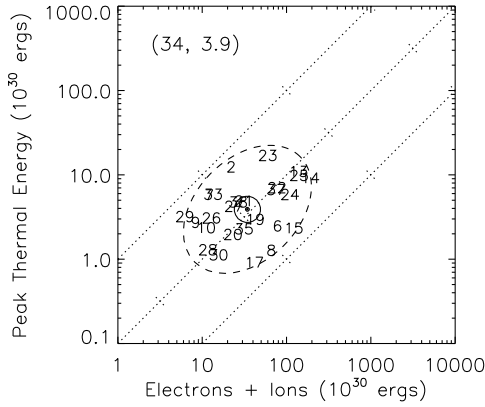
‡ Spearman’s rank correlation coefficient – a non-parametric measure of statistical dependence between two variables – see Equation (A6).



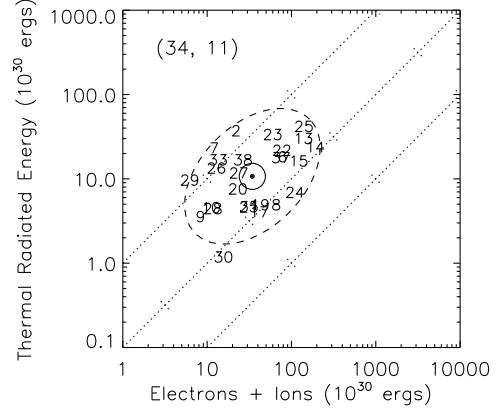
(a) GOES 1–8 Å band vs. the total energy radiated from the SXR-emitting plasma.



(b) Total energy radiated from the SXR-emitting plasma vs. the peak thermal energy content of that plasma.

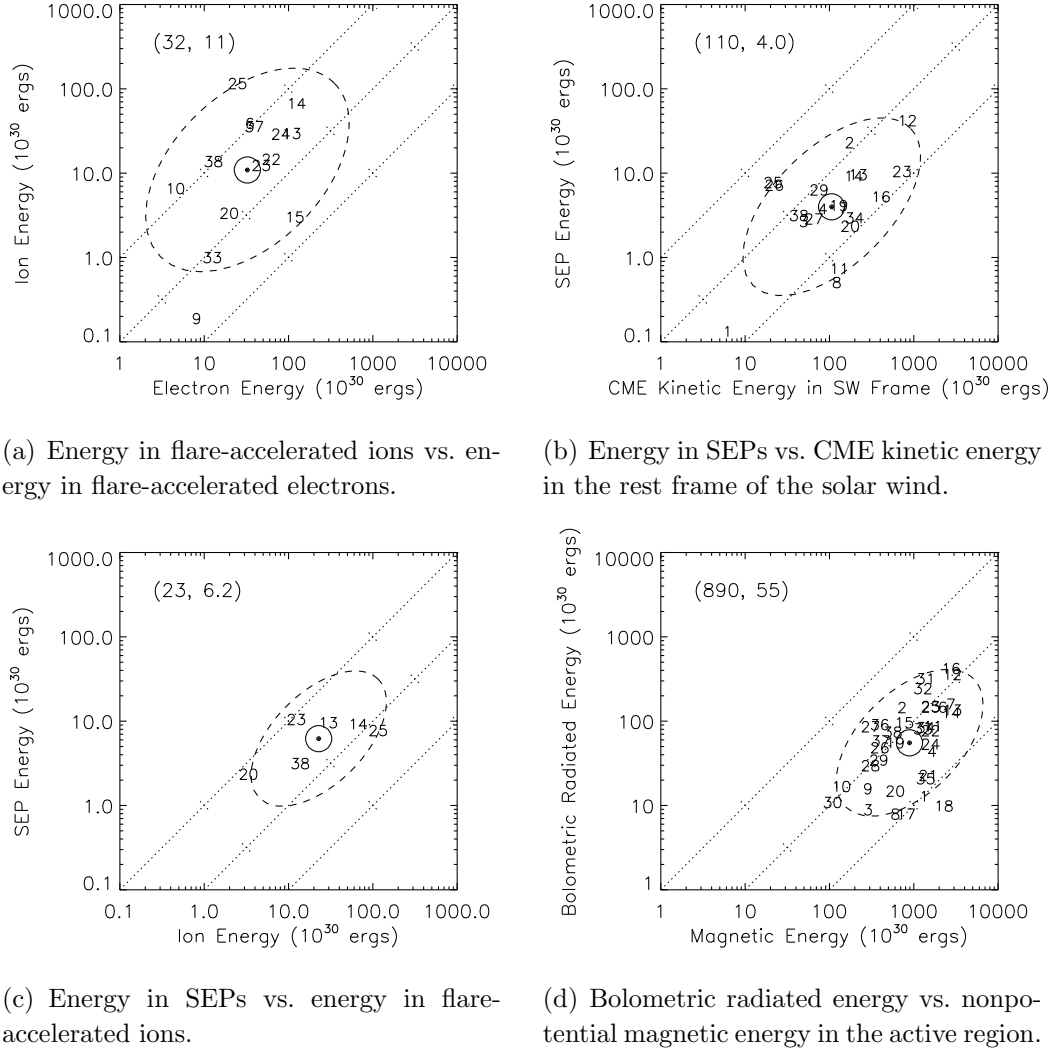


(c) Peak thermal energy in the SXR-emitting plasma vs. energy in flare-accelerated nonthermal particles (electrons plus ions when available).



(d) Thermal radiated energy from the SXR-emitting plasma vs. the energy in flare-accelerated nonthermal particles (electrons plus ions when available).

Fig. 1.— Scatter plots of different energy components, in units of 10^{30} ergs. Each plot includes all events for which measurements are available for both components. The point for each event is labeled by its event number (Table 1) and is located at the center of each number. The location of the logarithmic centroid, defined by Equation (A1), for all the events in the plot is shown by a bullseye with its X and Y coordinates listed in the upper left corner of the plot. The three diagonal dashed lines represent the 1%, 10% and 100% ratios between the plotted components. Lines of constant logarithmic average event energy are shown by dashes every order of magnitude along the lines of constant ratio. The major and minor axes of the ellipse are defined by ± 2 times the RMS deviation of the points respectively parallel (Equation (A5)) and perpendicular (Equation (A4)) to the line of constant ratio passing through the centroid (see text and Appendix for discussion). Points outside this ellipse are considered as outliers and are discussed in Section 5.



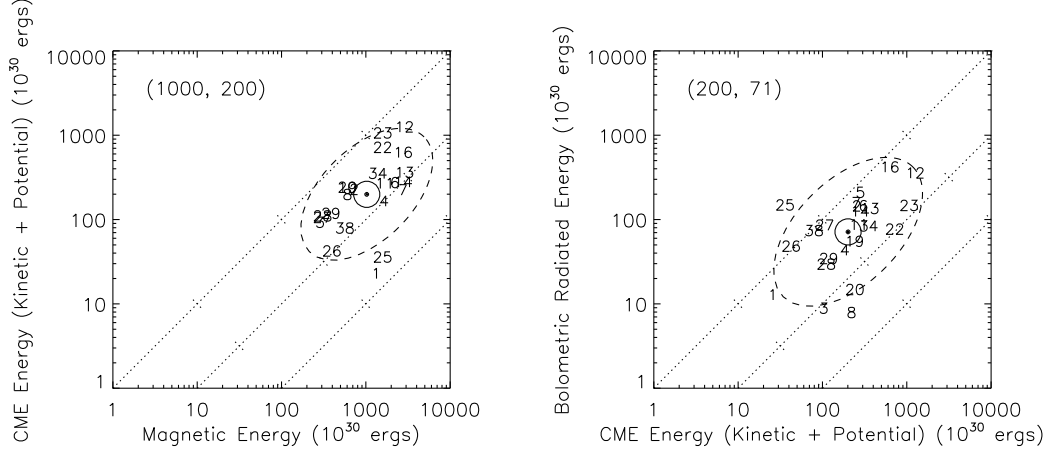
(a) Energy in flare-accelerated ions vs. energy in flare-accelerated electrons.

(b) Energy in SEPs vs. CME kinetic energy in the rest frame of the solar wind.

(c) Energy in SEPs vs. energy in flare-accelerated ions.

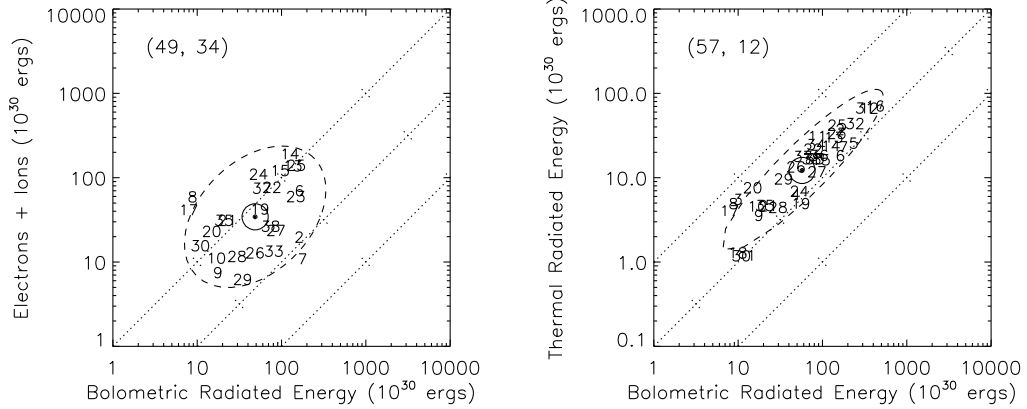
(d) Bolometric radiated energy vs. nonpotential magnetic energy in the active region.

Fig. 2.— Same as Figure 1 for different combinations of energy components, as indicated on the axis labels.



(a) CME total energy (kinetic + potential, in the rest frame of the Sun) vs. the free (nonpotential) magnetic energy of the active region.

(b) Bolometric radiated energy vs. the CME total energy (kinetic + potential, in the rest frame of the Sun).



(c) Energy in flare-accelerated nonthermal particles (electrons and ions) vs. bolometric radiated energy.

(d) Total energy radiated by SXR-emitting plasma vs. bolometric radiated energy.

Fig. 3.— Same as Figure 1 for different combinations of energy components, as indicated on the axis labels.

nevertheless a reasonable bunching of the points. The maximum spread of the points is less than two orders of magnitude in either parameter. On average, the energy in the flare-accelerated non-thermal particles exceeds the peak thermal energy by almost an order of magnitude ($R = 0.11$), indicating that there is sufficient power in the particles to create the SXR-emitting thermal plasma. This conclusion is reinforced by the fact that the energy in the particles is a lower limit (see Sections 2.4 and 2.5). This result is in agreement with earlier comparisons of these two components - see, e.g., de Jager et al. (1986) and Saint-Hilaire & Benz (2002).

3.4. Thermal Radiated Energy vs. Energy in Flare-Accelerated Nonthermal Particles

Figure 1d shows the scatter plot for the total energy radiated by the SXR-emitting thermal plasma vs. the energy in flare-accelerated nonthermal particles (electrons and ions when available). This figure combines information already evident in Figure 1b and Figure 1c. It shows that the energy in accelerated electrons and ions during a flare is not only sufficient to supply the peak energy of the SXR-emitting plasma (Figure 1c), but it is also high enough (by a factor of ~ 3 , $R = 0.31$) to account for the radiation from this plasma throughout the event. It follows that a significant fraction of the energy in flare-accelerated nonthermal particles is deposited in lower-temperature plasma and ultimately radiated in optical and EUV wavebands (see Emslie et al. 2005). Again, Event #30 (the M6.4 event on 2005 August 25) is the only “outlier” in this plot, reflecting the low values of both the thermal and nonthermal energy components.

3.5. Flare-Accelerated Ions vs. Electrons

Figure 2a shows the scatter plot for the energy in flare-accelerated ions, as determined from the *RHESSI* gamma-ray observations (Section 2.5), vs. the energy in flare-accelerated electrons, as determined from *RHESSI* hard X-ray observations (Section 2.4).

As pointed out in Section 2.4, the energy in electrons is critically dependent in the low-energy cutoff, $E_{\min}$, that is assumed for the electron spectrum. Since the largest value of $E_{\min}$ that gives an acceptable fit to the data is used for each spectrum, the total electron energy values are lower limits with order-of-magnitude uncertainties. As explained in Section 2.5, the situation for the ion energies is even worse because of the need to extrapolate the ion flux at energies above 30 MeV, as derived from the 2.223 MeV line fluences, to the ion flux above

1 MeV, resulting in an almost three-order-of-magnitude range in the ion energies. Because of these large uncertainties in both the electron and ion energies, there is a much wider scatter than in the plots in Figure 1. However, with some notable exceptions that have almost two orders of magnitude more energy in the electrons than in the ions (Events #9 and #15), the electron and ion energies are generally comparable within an order of magnitude. This result is in agreement with the claims by Ramaty et al. (1995) and Ramaty & Mandzhavidze (2000) and has significant consequences for acceleration models.

3.6. SEP Energy vs. CME Kinetic Energy in the Solar Wind Rest Frame

Figure 2b shows the scatter plot for the energy in the accelerated SEP population vs. the kinetic energy of the CME in the rest frame of the solar wind. We use the solar wind rest frame since a shock can be formed and SEPs accelerated only if the CME is traveling at least as fast as the solar wind speed (Mewaldt et al. 2008b). Lacking knowledge of the solar wind speed low in the corona for each event, we have simply subtracted 400 km s^{-1} from the measured CME speed in order to estimate the kinetic energy available for accelerating particles via shock acceleration.

In Figure 2b, most of the SEP values cluster between 1% and 10% of the CME kinetic energy. Comparing the nine events that are common to both this study and that of Mewaldt et al. (2008a), the SEP/CME ratio was $\sim 6\%$ in the 2008 study, and is $\sim 4\%$ ($R = 0.04$) in this study. Thus, adopting the longitude correction of Lario et al. (2006) does not significantly affect the average SEP energy content deduced for the 2002 – 2006 events. This result confirms that the SEP energy is a small, but not insignificant, fraction of the CME kinetic energy in most large events.

3.7. SEP Energy vs. Energy in Flare-Accelerated Ions

Figure 2c shows the scatter plot for the total energy in SEPs vs. the energy in flare-accelerated ions, as determined from *RHESSI* gamma-ray observations. There are only a limited number of events that can be compared but in those few cases there is comparable energy in the ions and SEPs ($R = 0.27$). At first sight, this appears to conflict with the study by Mewaldt (2012, in preparation) that shows the number of SEP protons $>30 \text{ MeV}$ is generally much higher than the number of $>30 \text{ MeV}$ protons accelerated in the flare. However, this difference can be accounted for in a number of ways. First, as noted in Section 2.5, the inferred energy in flare-accelerated ions is based on a very uncertain spectral

extrapolation over more than an order of magnitude in proton energy (from 30 MeV down to 1 MeV). To obtain the energy in flare-accelerated ions (Section 2.5), we have assumed a spectral index of 4, which results in a significantly higher total energy than would be obtained if the extrapolation was performed with the much lower spectral indices representative of SEP spectra. Further, for the well-observed 2003 October 28 flare (Event #12), we obtained an ion spectral index of 3.4 at energies between ~ 3 and 50 MeV, so that the energy content in ions could be significantly lower than we have used here, especially if the spectrum hardens even more between, say, 1 and 20 MeV, a feature that is clearly seen in SEP spectra. Second, SEP protons typically carry $\gtrsim 80\%$ of the SEP ion energy, whereas flare-accelerated protons carry only about one-third of the ion energy.

3.8. Bolometric Radiated Energy vs. Magnetic Energy

Figure 2d shows the scatter plot for the bolometric radiated energy vs. the nonpotential (free) magnetic energy in the active region. Here we have a relatively tight bunching with little more than 1.5 orders of magnitude range in each parameter. It should be emphasized that the plotted bolometric radiated energies are, with the exception of the five events noted in Table 1, not directly measured but rather estimates made using the FISM model (Chamberlain et al. 2007, 2008), and the magnetic energy is only good to an order of magnitude. With this proviso, we find that the average bolometric radiated energy is $\sim 7\%$ of the free magnetic energy ($R = 0.07$), and in all cases the available magnetic energy exceeds the bolometric radiated energy by at least half an order of magnitude. This is consistent with the well-accepted notion that the reservoir of magnetic energy is sufficient to power the main components of the flare.

3.9. CME Energy vs. Magnetic Energy

Figure 3a shows the scatter plot for the CME total energy (potential + kinetic) in the rest frame of the Sun vs. the nonpotential energy in the magnetic field. Similar to the plot of bolometric energy vs. magnetic energy (Figure 2d), the CME energy is, on average, almost an order of magnitude less than the magnetic energy ($R = 0.21$). While bearing in mind the very approximate values of the latter, it nevertheless appears, from the results of this and the previous subsection, that much of the available magnetic energy (some two-thirds) is retained in the active region (i.e., the field does not return to a fully potential state), even after the flare and the ejection of the CME. This result is consistent with the generous limits established by Moore et al. (2012) on the possible free energy that an active region magnetic

field can hold before it erupts.

3.10. Bolometric Radiated Energy vs. CME Energy

Figure 2d and 3a show, respectively, that the available magnetic energy is about 15 times the bolometrically radiated energy in the flare ($R = 0.07$) and about 5 times the CME energy ($R = 0.21$). This indicates that, on average, the energy in the CME is larger than the energy radiated by a factor of ~ 3 . Figure 3b confirms this result by showing the scatter plot for bolometric radiated energy vs. the CME total energy (kinetic + potential). On average, the bolometric energy is indeed about half an order of magnitude less than the CME energy ($R = 0.35$).

3.11. Flare-Accelerated Particle Energy vs. Bolometric Radiated Energy

Figure 3c shows the scatter plot for the total energy in flare-accelerated particles (electrons plus ions) vs. the bolometric radiated energy. This figure shows that the energy in accelerated particles during a flare is comparable to the total bolometric radiated energy from the flare ($R = 0.71$), with the ratio being greater than unity in some events and less than unity in others. It must be recalled that while the bolometric radiated energies are accurate to within a factor of ~ 2 to 3 , the energies in flare-accelerated particles are uncertain to at least an order of magnitude. The energies in electrons are most probably lower limits and may well underestimate the true energy content by up to an order of magnitude. The energies in ions may, however, be overestimates, depending on the power-law index used for the spectral extrapolation. We can tentatively conclude, however, that there is sufficient energy in the flare-accelerated particles to account for *all* the energy radiated in the flare. However, this conclusion must somehow be verified by more accurate estimates of the energy in the flare-accelerated electrons and ions.

3.12. Energy Radiated by Soft X-Ray Emitting Plasma vs. Bolometric Energy

Figure 3d shows the scatter plot for the total energy radiated by SXR-emitting plasma vs. the bolometric radiated energy. The relatively tight correlation ($\rho = 0.92$) is to a large extent due to the fact that most of the bolometric radiant energies were computed using the FISM model, which uses the radiated energy from SXR-emitting plasma to estimate the bolometric energy. Nevertheless, the data show that only about one-fifth of the bolometric

energy radiated by a flare is radiated by the SXR-emitting plasma ($R = 0.21$).

4. Discussion

The comparisons of the energetics of the different components shown in the scatter plots of Figures 1–3 are summarized in Table 3. In attempting to draw any definitive conclusions from these comparisons, we must keep in mind the limitations of our analysis. The events in our list cover the period from *RHESSI*’s launch in February 2002 through 2006. They include the largest SEP events and all *RHESSI* gamma-ray events, and hence represent events where a significant number of ions were accelerated to high energies, either in the flare, at the CME shock, or at both locations. Thus, we have concentrated on those events where particle acceleration at the Sun and in interplanetary space has been the most efficient. We include nine of the eleven X5 or greater events that occurred in this time period, or about 0.1% of the over 10,000 $>A1$ events in the GOES event list. Most of the CMEs that we have included have kinetic energies of $\gtrsim 10^{32}$ erg, and according to Gopalswamy (2006), only $\sim 0.5\%$ of all CMEs recorded by SOHO from 1996 through 2003 had kinetic energies this large (the average energy was 5×10^{29} erg).

Despite the relatively large number of events in our list, the range of energies is only about two orders of magnitude in any of the energy components. The uncertainties on the energy estimates of each component are generally at least an order of magnitude, except for the few cases where the bolometric radiated energy is measured with an accuracy of a factor of ~ 2 . Thus, in most cases, we cannot expect to see any significant trends with the size of the events over the limited range of our selected events. In spite of these selection effects and measurement limitations, the scatter plots nevertheless reveal several useful results regarding large SEEs in general and about specific events in particular. With a few notable exceptions (see Section 5), the points in each plot are bunched together within the expected order-of-magnitude uncertainties. However, there is substantially more scatter of the points in some parameters than others. Only a few events stand out as outliers in certain plots; these outliers are discussed in Section 5 below.

The general bunching of the data points in each scatter plot is characterized by the logarithmic RMS deviations parallel and perpendicular to the line of constant ratio that passes through the logarithmic centroid. The X and Y values of the centroids are shown on each plot and listed along with the RMS values in Table 3. The fact that the data points generally bunch together can be interpreted as an extension to SEEs of the “*big flare syndrome*” (BFS), a phrase coined by Kahler (1982) based on the strong correlations between proton fluxes and associated microwave and hard X-ray burst parameters, and a

concept which has since come to mean that each flare component scales roughly linearly with some absolute measure of flare “size.” At that time, before the so-called “*solar flare myth*” was exposed (Gosling 1993), it was not clear that SEPs were generally more likely to be accelerated at CME shock fronts, but now the same concept can be applied to include CMEs with flares and SEPs. From our data, it is clear that, with some caveats, the BFS concept can be applied to all energetic SEE phenomena, including the CME energy.

Notable exceptions to the scatter of the points being consistent with the expected uncertainties in each parameter are the following:

- The plot of the GOES 1 – 8 Å integrated energy vs. the total energy radiated from the SXR-emitting plasma over all wavelengths (Figure 1a) shows that these two parameters are well correlated (the Spearman’s rank correlation coefficient ρ given in Table 3 is 0.96, the highest for any pair of parameters). This is not surprising since the measurements of the two parameters are not independent – they both use the same GOES X-ray data. The scatter of the points thus reflects only the range of flare sizes and the different temperatures – the scatter perpendicular to the line of constant ratio, only about half an order of magnitude, is the result of different temperatures, while the scatter parallel to that line is almost two orders of magnitude, reflecting the range of flare intensities. A regression analysis of the data in Table 1 shows that the ratio (best estimate $\pm$ standard error) of the total energy radiated by SXR-emitting thermal plasma in the flare to the observed GOES 1 – 8 Å flux is 15.4 ± 0.8 , i.e., that the energy radiated in the GOES 1 – 8 Å band is about one-fifteenth to one-twentieth ($R = 0.05$) of the total energy radiated by the SXR-emitting plasma over all wavelengths. The presence of the outlier points for Events #3 and #8, several RMS values away from the line of constant ratio, suggests that these two events are different in that their temperature is lower than the average.
- The range of the ion energies – about three orders of magnitude – is larger than for all other parameters. This is evident in Figure 2a, which shows the scatter plot for the energy in flare-accelerated ions as determined from the *RHESSI* gamma-ray observations (Section 2.5) vs. the energy in flare-accelerated electrons as determined from *RHESSI* hard X-ray observations (Section 2.4). While it may be noted that Shih et al. (2009) found a stronger correlation, over more than three orders of magnitude, between the energy in flare-accelerated ions and the energy in electrons above 300 keV (rather than the ~ 20 keV lower cutoff energy used here), it must nevertheless again be stressed that the principal driver of this large range of values is the large uncertainty in the ion energy content above 1 MeV, a quantity derived through spectral extrapolation over one-and-a-half orders of magnitude in ion energy (Section 2.5).

5. Discussion of Outlier Data Points

While most of the events in Table 1 lie (by definition) within the 2σ ellipses in the various cross-correlation plots, there are a few notable exceptions. We now discuss these “outliers” and the possible reasons for their unusual energetic partitioning.

- Event #1. This M5.1 event, on 2002 February 20, is one of the two events with a relatively low ratio of CME energy (kinetic + potential) to magnetic energy (Figure 3a). Table 1 shows a paucity of data for other energetic components. Data for GOES 1 – 8 Å emission and total radiated energy from the SXR-emitting plasma are available; the event does fall outside the 2σ ellipse in Figure 1a, but only by virtue of its overall weakness, not the ratio of GOES 1 – 8 Å emission to total SXR-emitting energy. We believe that this is therefore simply a weak event, in which only a small fraction of the available magnetic energy was dissipated.
- Event #3. This C5 event, on 2002 May 22, has a relatively low ($\lesssim 1\%$) ratio of GOES 1 – 8 Å emission to total SXR-emitting energy (Figure 1a). An event with limited overall information, it does, however, appear in Figure 2b, where a normal ratio of SEP to CME energy is evident. It should be noted that this is the only GOES C-class event in Table 1 and we therefore simply categorize this event as a weak GOES event, possibly due to the low temperature (< 9 MK) of the soft-X-ray-emitting plasma. This C5 event is the third in a sequence of events starting with an M1.5 event peaking at 21:29 UT on May 21, followed by a C9.7 event at 00:30 on May 22 and the C5 event at 03:34 UT. *RHESSI* saw parts of each of these events and the 6-12 keV images show that they came from three distinctly different locations with the following spatial centroid coordinates (in arcseconds): (-550, 270), (880, -330), (750, -350), respectively. The peak temperatures derived from the GOES data for the three events are 13, 11, and 8 MK, respectively. Thus, this event was much cooler than the other larger events in our list.
- Event #9. This X1.4 event, on 2003 May 27, has the lowest ratio of flare-accelerated ion energy to flare-accelerated electron energy (Figure 2a). The ratios of peak thermal energy and broad-band SXR radiated energy to energy in flare-accelerated nonthermal particles are average (Figures 1c and 1d), and the ratio of GOES 1 – 8 Å to total SXR-emitting energy is nominal (Figure 1a). Shih et al. (2009) show that this flare has a ratio of accelerated $\gtrsim 20$ MeV nucleon $^{-1}$ ions to accelerated relativistic electrons that is comparable to other gamma-ray flares, suggesting that this flare is an outlier because it has a relative deficiency in higher-energy particles, both ions and electrons. In particular, the stated ion energy content may be a significant underestimate if there are

many more low-energy ions than based on the single power-law spectrum extrapolation from the high-energy proton flux value obtained from the neutron-capture line flux.

- Event #12. This X17 event, on 2003 October 28, has relatively high CME and magnetic energies (Figure 3a and Table 1). It was one of three events from the “Halloween” active region of October-November 2003, in which a very high non-potential magnetic energy value (4×10^{33} ergs; see Figure 2d) was inferred. This event is therefore an “outlier” simply because it was a very large event; there are no particularly unusual ratios of energetic components.
- Event #25. For this X7.1 event, on 2005 January 20, the ratios of nonthermal particle energy to bolometric radiated energy (Figure 3c), soft-X-ray-radiated to peak thermal energy (Figure 1b), and soft-X-ray-radiated to nonthermal particles (Figure 1d) are normal. However, the ion to electron energy ratio ($\sim 5 : 1$; Figure 2a and Table 1) is conspicuously high; indeed, this event had one of the highest ion energy contents measured. The event also has a very low ratio of CME energy to magnetic energy (Figure 3a), but a very high ratio of SEP energy to CME energy (Figure 2b). The ratio of bolometric radiated energy to free magnetic energy is nominal (Figure 2d), but it is the only event with a ratio of bolometric radiated energy to CME energy that is greater than 100% (Figure 3b). Together, these results show that the main component that makes this event an “outlier” is the low CME energy. Note, however, that the CME kinetic energy in this event is very uncertain.

The reasons for these unusual circumstances are not completely understood. Much has been written about this event (e.g., Grechnev et al. 2008, and references therein) but the acceleration of the intense flux of SEPs has still not been fully resolved. It has been suggested that in this event the SEPs were accelerated at the flare site rather than in the CME shock (Lin 2005a,b). In similar vein, Simnett (2006, 2007) concluded that, “the relativistic protons were not accelerated by the CME-driven shock.” The event produced a cosmic-ray ground-level enhancement that is among the largest recorded in the history of cosmic ray measurements (Mishev et al. 2011). However, based on the particle spectrum measured over a wide rigidity range (1 - 20 GV), Morgan & Lopate (2008) state that, “The 2005 January 20 GLE was an unusual event in its intensity and brevity, placing it on the outer edges of parameter space for shock acceleration to GeV energies, but still not requiring a different process, i.e., direct solar-flare acceleration.” On the other hand, Moraal & McCracken (2011) conclude that neutron monitor observations of this event indicate two separate pulses of high-energy particles, one accelerated by the flare, and a second accelerated by the CME-driven shock.

- Event #30. This M6.4 event, on 2005 August 25, had a very low peak thermal energy

content and a relatively low ratio of the total SXR-emitted energy to the peak thermal energy content (Figure 1b). It also has a low ratio of total SXR-emitted energy to nonthermal particle energy (Figure 1d). No CME or SEP data are available for this event. For this event, the GOES flux decayed from the M6.4 peak to the C1 background level in only ~ 30 minutes, so that the low values of the radiated energy in SXR-emitting plasma are due to this simply being a relatively short-lived event.

6. Conclusions

Despite the rather large uncertainties in the individual measurements used in this analysis, the relatively large number (38) of events nevertheless allows us to reach some general conclusions about the “typical” ratios of various energetic components in large SEEs. We have found the following general statements to hold:

- The total energy radiated by the SXR-emitting plasma over the course of the event exceeds, by about half an order of magnitude ($R = 2.8$ in Table 3), the peak energy content of the thermal plasma that produces this radiation. This reinforces the conclusions of Moore et al. (1980) that some form of energy is continuously supplied to this hot plasma throughout the event;
- The energy content in flare-accelerated particles (electrons and ions) is sufficient to create not only the total energy radiated by the SXR-emitting plasma, but also the total bolometric radiated energy of the event;
- The energy contents of flare-accelerated ions and electrons are comparable at the order of magnitude level. This result supports the earlier claims of Ramaty et al. (1995) and Ramaty & Mandzhavidze (2000) and has significant consequences for acceleration models;
- The SEP energy is typically a few percent ($R = 0.04$ in Table 3) of the CME kinetic energy in the solar wind rest frame, a result with implications for shock-acceleration models of interplanetary particles;
- The available magnetic energy is indeed sufficient to power the CME, the flare-accelerated particles, and the hot thermal plasma. Although some “double-counting” may be involved in summing these energy components (e.g., both the flare-accelerated particles and the CME may transfer energy to the ambient plasma; see Emslie et al. 2005), this result nevertheless conforms to the widely-held view that the source of the energy released in SEEs lies in stressed magnetic fields.

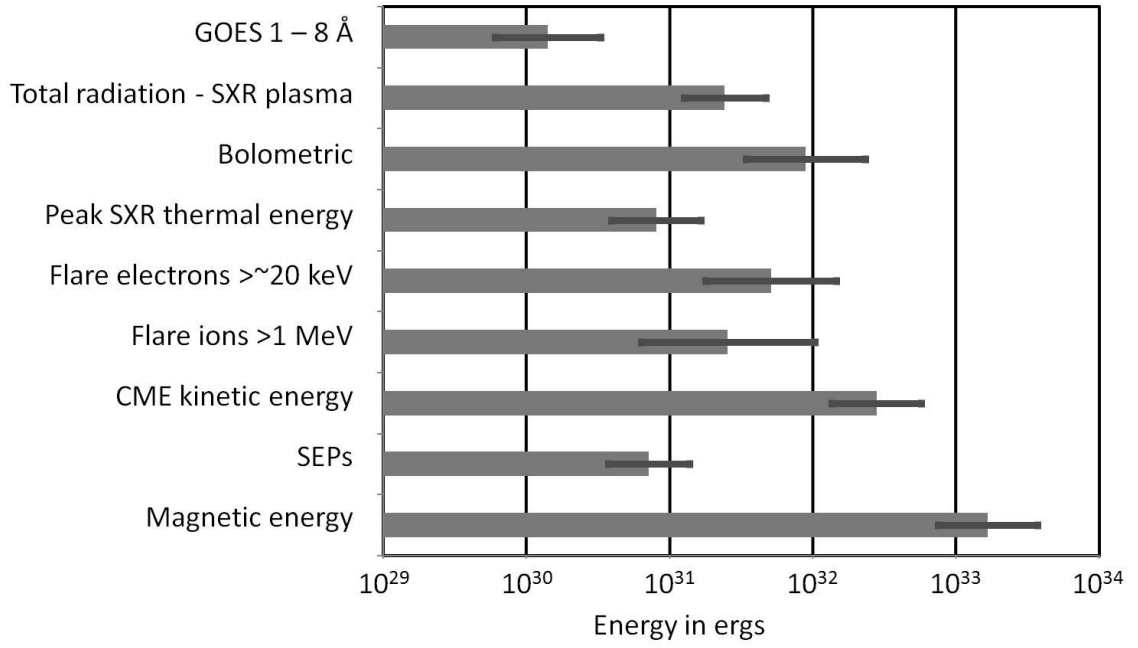


Fig. 4.— Bar chart showing the average energies of the different components for the six events for which values were obtained for all components – Events #13, 14, 20, 23, 25, and 38. The short thin bars show the $\pm 1\sigma$ logarithmic scatter of the energies of the six events.

Figure 4 shows the average energies (with $\pm 1\sigma$ logarithmic scatter) of the various energetic components for the six events (Events #13, 14, 20, 23, 25, 38) for which *all* energetic components were measured (Events #6 and #12 were not included, since for these events some of the components were determined only as upper or lower limits – see Table 1). This figure, coupled with the overall ratios summarized in Table 3, succinctly demonstrates how, in very approximate terms, the available magnetic energy gets distributed in a “typical” flare in our sample:

1. Of the $\sim 10^{33}$ ergs of available non-potential magnetic energy, approximately 30% is released in the SEE, with the remainder staying in the active region as stored magnetic energy. Of the $\sim 30\%$ that is released, some 80% ($\sim 25\%$ of the available energy) is released in the CME (mostly as kinetic energy) and approximately 20% ($\sim 5\%$ of the available energy) is released as flare-accelerated particles, roughly evenly distributed between electrons and ions.
2. All of the energy in the flare-accelerated particles appears to ultimately emerge as radiation across a wide range of wavelengths, from optical to soft X-rays (Emslie et al. 2005). However, only $\sim 30\%$ of the energy in flare-accelerated particles ($\sim 2\%$ of the available stored energy) is ultimately radiated from high-temperature soft X-ray-emitting plasma. The maximum amount of energy stored as enhanced thermal energy in the soft X-ray-emitting plasma is less than 1% of that released, and the amount of energy radiated in the diagnostic GOES 1–8 Å waveband is only about 5% of the total energy radiated by the SXR-emitting plasma, or $\sim 0.1\%$ of the available magnetic energy.
3. Because of the need for a CME to “overtake” the solar wind and form a shock front where SEPs can be accelerated, only about two-thirds of the kinetic energy carried by the CME ($\sim 15\%$ of the available nonpotential magnetic energy) is available for SEP acceleration. The SEP production process is in turn $\sim 4\%$ efficient, so that only about half a percent of the released magnetic energy ultimately appears in the form of SEPs.

Although for completeness we have listed Spearman’s rank correlation coefficient (ρ) values in Table 3, little significance can be attached to these values other than for the obviously tight correlations between parameters that are essentially derived from the same data (e.g., the bolometric emission, the energy radiated from the SXR-emitting plasma, and the energy radiated in the GOES 1 – 8 Å band, all of which are dependent on GOES SXR flux measurements). Any correlations amongst independent components are masked by the large uncertainties in the individual measurements used in the various scatter plots.

Progress in this direction will require sampling of events over a much larger range in flare size to determine if the distribution of energies amongst the different components found here for large events is preserved for smaller events, as would be expected for a “*big SEE syndrome*.” Such a project is the next step towards a more comprehensive understanding of energy release in SEEs.

Using data from the new, more sophisticated, instruments that are now available will allow more accurate energy estimates to be made of some of the components. For example, the detailed differential emission measure analysis now possible using data from the EUV Imaging Spectrometer (EIS; Culhane et al. 2007) on Hinode, and from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) and the Extreme Ultraviolet Variability Experiment (EVE; Woods et al. 2012) on the Solar Dynamics Observatory (SDO), should lead to better estimates of the energies in the thermal plasma. Vector magnetograms from the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) on SDO allow for more accurate estimates of the energy in the nonpotential magnetic field.

Other energy components not considered in our analysis may be found to contain significant total energy and should be included in any future compilation of global energetics. These include the turbulent mass motions revealed by the broadening of atomic lines seen with EUV and X-ray spectrometers (e.g., Phillips et al. 2008), and the cumulative heating of CME plasma reported by Murphy et al. (2011) to be comparable to (or even greater than) the CME kinetic energy. Another aspect not discussed here is the question of a second flare phase that, according to Woods et al. (2011) and Su et al. (2011), can release a similar amount of energy as in the initial phase. Nevertheless, we believe that the order-of-magnitude comparisons of energetic components presented herein represents a significant advance in our understanding of the nature of energy release in SEEs.

We thank Gordon Holman, Richard Schwartz, and Kim Tolbert for help with analyzing the GOES and *RHESSI* data, and Anil Gopie for doing most of the GOES data analysis. AGE was supported by NASA Grant NNX10AT78J, RAM by NASA grants NNX08AI11G and NNX11AO75G, and AV by various NASA grants to the Naval Research Laboratory. SoHO is a joint ESA and NASA mission. CHIANTI is a collaborative project involving researchers at NRL (USA), RAL (UK), and the Universities of Cambridge (UK), George Mason (USA), and Florence (Italy).

A. Appendix

Here, for definiteness, we provide the equations used to determine the values listed in Table 3: the (logarithmic) centroid energies $X_{centroid}$ and $Y_{centroid}$, their ratio R , the RMS (1σ) values both perpendicular and parallel to the lines of constant ratio, and the Spearman’s rank correlation coefficient ρ .

The coordinates of the logarithmic centroid in each plot are given by

$$\begin{aligned}\log_{10} X_{centroid} &= \frac{1}{N} \sum_{i=1}^N \log_{10} X_i ; \\ \log_{10} Y_{centroid} &= \frac{1}{N} \sum_{i=1}^N \log_{10} Y_i ,\end{aligned}\tag{A1}$$

where N is the number of events for which there are viable measures of both components included in the scatter plot in question.

The lines of constant ratios ($R = 100\%$, 10% , and 1%) between the X and Y components satisfy the following relation:

$$\begin{aligned}R &= Y/X \\ \text{or } \log_{10} R &= \log_{10}(Y/X) \\ &= \log_{10} Y - \log_{10} X .\end{aligned}\tag{A2}$$

Lines of constant logarithmic average event energy ($\log_{10} A$), shown in the plots as dashes every order of magnitude along the lines of constant ratio, are defined as follows:

$$\begin{aligned}\log_{10} A &= (\log_{10} X + \log_{10} Y)/2 \\ &= \log_{10} \sqrt{XY} .\end{aligned}\tag{A3}$$

The RMS deviations of the points perpendicular to and parallel to the line of constant ratio passing through the centroid are defined by

$$\begin{aligned}RMS_{\perp} &= (1/N) \sqrt{\sum_i (\log_{10} R_i - \log_{10} R_{centroid})^2} \\ &= (1/N) \sqrt{\sum_i (\log_{10}(Y_i/X_i) - \log_{10}(Y_{centroid}/X_{centroid}))^2}\end{aligned}\tag{A4}$$

and

$$RMS_{\parallel} = (1/N) \sqrt{\sum_i (\log_{10} A_i - \log_{10} A_{centroid})^2}$$

$$= (1/2N) \sqrt{\sum_i [\log_{10}(X_i Y_i) - \log_{10}(X_{centroid} Y_{centroid})]^2} . \quad (\text{A5})$$

These RMS values were used to draw the ellipse with axes of $2 \times \text{RMS}_\perp$ and $2 \times \text{RMS}_\parallel$ around the logarithmic centroids in each plot.

The Spearman’s rank correlation coefficient ρ is calculated by first assigning ranks x_i ($= 1, \dots, N$) and y_i ($= 1, \dots, N$) to the X and Y values, respectively, of the N points used in the plot in question. The ranks are assigned such that $X(x_i) \leq X(x_{i+1})$, $Y(y_i) \leq Y(y_{i+1})$, with “ties” assigned the average rank of the tied values. (Note that the rank order does not depend on whether we use the X_i values or their logarithms $\log_{10} X_i$.) The Spearman’s rank correlation coefficient is then calculated as the correlation coefficient of the ranks:

$$\rho = \frac{\sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^N (x_i - \bar{x})^2 \sum_{i=1}^N (y_i - \bar{y})^2}} , \quad (\text{A6})$$

where $\bar{x}$ and $\bar{y}$ are the means of the ranks x_i and y_i , respectively. For a monotonic dependence of Y on X , $\rho = 1$, even if the variables do not obey a perfect linear correlation.

REFERENCES

- Band, D., Matteson, J., Ford, L., et al. 1993, *ApJ*, 413, 281
- Bobra, M. G., van Ballegoijen, A. A., & DeLuca, E. E. 2008, *ApJ*, 672, 1209
- Brown, J. C. 1973, *Sol. Phys.*, 28, 151
- Brueckner, G. E., Howard, R. A., Koomen, M. J., et al. 1995, *Sol. Phys.*, 162, 357
- Caspi, A. 2010, PhD thesis, Department of Physics, University of California, Berkeley, CA 94720-7450, USA
- Caspi, A., & Lin, R. P. 2010, *ApJ*, 725, L161
- Chamberlin, P. C., Woods, T. N., & Eparvier, F. G. 2007, *Space Weather*, 50, 7005
- . 2008, *Space Weather*, 60, 5001
- Chollet, E. E., Giacalone, J., & Mewaldt, R. A. 2010, *Journal of Geophysical Research (Space Physics)*, 115, 6101

- Cohen, C. M. S., Stone, E. C., Mewaldt, R. A., et al. 2005, *Journal of Geophysical Research (Space Physics)*, 110, 9
- Cook, W. R., Cummings, A. C., Cummings, J. R., et al. 1993, *IEEE Transactions on Geoscience and Remote Sensing*, 31, 557
- Culhane, J. L., Harra, L. K., James, A. M., et al. 2007, *Sol. Phys.*, 243, 19
- de Jager, C., Bruner, M. E., Crannell, C. J., et al. 1986, *NASA Conf. Pub.*, 2439, 5.5
- Dennis, B. R., & Pernak, R. L. 2009, *ApJ*, 698, 2131
- Dere, K. P., Landi, E., Mason, H. E., Monsignori Fossi, B. C., & Young, P. R. 1997, *A&AS*, 125, 149
- Dere, K. P., Landi, E., Young, P. R., et al. 2009, *A&A*, 498, 915
- Emslie, A. G., Dennis, B. R., Holman, G. D., & Hudson, H. S. 2005, *Journal of Geophysical Research (Space Physics)*, 110, 11103
- Emslie, A. G., Kucharek, H., Dennis, B. R., et al. 2004, *Journal of Geophysical Research (Space Physics)*, 109, A10104
- Gold, R. E., Krimigis, S. M., Hawkins, III, S. E., et al. 1998, *Space Sci. Rev.*, 86, 541
- Gopalswamy, N. 2006, *Journal of Astrophysics and Astronomy*, 27, 243
- Gosling, J. T. 1993, *J. Geophys. Res.*, 98, 18937
- Grechnev, V. V., Kurt, V. G., Chertok, I. M., et al. 2008, *Sol. Phys.*, 252, 149
- Guo, Y., Ding, M. D., Wiegelmann, T., & Li, H. 2008, *ApJ*, 679, 1629
- Hua, X.-M., & Lingenfelter, R. E. 1987, *Sol. Phys.*, 107, 351
- Jiao, L., McClymont, A. N., & Mikic, Z. 1997, *Sol. Phys.*, 174, 311
- Kahler, S. W. 1982, *J. Geophys. Res.*, 87, 3439
- Kiener, J., Gros, M., Tatischeff, V., & Weidenspointner, G. 2006, *A&A*, 445, 725
- Kontar, E. P., Brown, J. C., & McArthur, G. K. 2002, *Sol. Phys.*, 210, 419
- Kopp, G., & Lawrence, G. 2005, *Sol. Phys.*, 230, 91
- Lario, D., Kallenrode, M.-B., Decker, R. B., et al. 2006, *ApJ*, 653, 1531

- Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, *Sol. Phys.*, 275, 17
- Lin, R. P. 2005a, in *American Institute of Physics Conference Series*, Vol. 781, *The Physics of Collisionless Shocks: 4th Annual IGPP International Astrophysics Conference*, ed. G. Li, G. P. Zank, & C. T. Russell, 246–251
- Lin, R. P. 2005b, *Advances in Space Research*, 35, 1857
- Lin, R. P., Schwartz, R. A., Pelling, R. M., & Hurley, K. C. 1981, *ApJ*, 251, L109
- Lin, R. P., Dennis, B. R., Hurford, G. J., et al. 2002, *Sol. Phys.*, 210, 3
- Mason, G. M., Gold, R. E., Krimigis, S. M., et al. 1998, *Space Sci. Rev.*, 86, 409
- Mazzotta, P., Mazzitelli, G., Colafrancesco, S., & Vittorio, N. 1998, *A&AS*, 133, 403
- Metcalf, T. R., Jiao, L., McClymont, A. N., Canfield, R. C., & Uitenbroek, H. 1995, *ApJ*, 439, 474
- Metcalf, T. R., Leka, K. D., & Mickey, D. L. 2005, *ApJ*, 623, L53
- Metcalf, T. R., De Rosa, M. L., Schrijver, C. J., et al. 2008, *Sol. Phys.*, 247, 269
- Mewaldt, R. A. 2006, *Space Sci. Rev.*, 124, 303
- Mewaldt, R. A., Cohen, C. M. S., Labrador, A. W., et al. 2005, *Journal of Geophysical Research (Space Physics)*, 110, 9
- Mewaldt, R. A., Cohen, C. M. S., Giacalone, J., et al. 2008a, in *American Institute of Physics Conference Series*, Vol. 1039, *American Institute of Physics Conference Series*, ed. G. Li, Q. Hu, O. Verkhoglyadova, G. P. Zank, R. P. Lin, & J. Luhmann, 111–117
- Mewaldt, R. A., Cohen, C. M. S., Cook, W. R., et al. 2008b, *Space Sci. Rev.*, 136, 285
- Mewaldt, R. A., Looper, M. D., Cohen, C. M. S., et al. 2012, *Space Sci. Rev.*, 32
- Milligan, R. O., & Dennis, B. R. 2009, *ApJ*, 699, 968
- Mishev, A. L., Velinov, P. I. Y., Mateev, L., & Tassev, Y. 2011, *Advances in Space Research*, 48, 1232
- Moore, R., McKenzie, D. L., Svestka, Z., et al. 1980, in *Skylab Solar Workshop II*, ed. P. A. Sturrock, 341–409
- Moore, R. L., Falconer, D. A., & Sterling, A. C. 2012, *ApJ*, 750, 24

- Moraal, H., & McCracken, K. G. 2011, *Space Sci. Rev.*, 99
- Morgan, T., & Lopate, C. 2008, in *International Cosmic Ray Conference*, Vol. 1, *International Cosmic Ray Conference*, 285–288
- Müller-Mellin, R., Kunow, H., Fleißner, V., et al. 1995, *Sol. Phys.*, 162, 483
- Murphy, N. A., Raymond, J. C., & Korreck, K. E. 2011, *ApJ*, 735, 17
- Murphy, R. J., Kozlovsky, B., Share, G. H., Hua, X.-M., & Lingenfelter, R. E. 2007, *ApJS*, 168, 167
- Onsager, T., Grubb, R., Kunches, J., et al. 1996, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 2812, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, ed. E. R. Washwell, 281–290
- Phillips, K. J. H., Feldman, U., & Landi, E. 2008, *Ultraviolet and X-ray Spectroscopy of the Solar Atmosphere* (Cambridge University Press), 270–273
- Poland, A. I., Howard, R. A., Koomen, M. J., Michels, D. J., & Sheeley, Jr., N. R. 1981, *Sol. Phys.*, 69, 169
- Ramaty, R., & Mandzhavidze, N. 2000, in *IAU Symposium*, Vol. 195, *Highly Energetic Physical Processes and Mechanisms for Emission from Astrophysical Plasmas*, ed. P. C. H. Martens, S. Tsuruta, & M. A. Weber, 123
- Ramaty, R., Mandzhavidze, N., & Kozlovsky, B. 1996, in *American Institute of Physics Conference Series*, Vol. 374, *American Institute of Physics Conference Series*, ed. R. Ramaty, N. Mandzhavidze, & X.-M. Hua, 172–183
- Ramaty, R., Mandzhavidze, N., Kozlovsky, B., & Murphy, R. J. 1995, *ApJ*, 455, L193
- Rottman, G. J., Woods, T. N., & Sparn, T. P. 1993, *J. Geophys. Res.*, 981, 10667
- Saint-Hilaire, P., & Benz, A. O. 2002, *Sol. Phys.*, 210, 287
- Scherrer, P. H., Bogart, R. S., Bush, R. I., et al. 1995, *Sol. Phys.*, 162, 129
- Scherrer, P. H., Schou, J., Bush, R. I., et al. 2012, *Sol. Phys.*, 275, 207
- Schrijver, C. J., De Rosa, M. L., Metcalf, T. R., et al. 2006, *Sol. Phys.*, 235, 161
- Schrijver, C. J., De Rosa, M. L., Metcalf, T., et al. 2008, *ApJ*, 675, 1637
- Shih, A. Y., Lin, R. P., & Smith, D. M. 2009, *ApJ*, 698, L152

- Shih, A. Y.-M. 2009, PhD thesis, University of California, Berkeley
- Simnett, G. M. 2006, *A&A*, 445, 715
- . 2007, *A&A*, 472, 309
- Stone, E. C., Cohen, C. M. S., Cook, W. R., et al. 1998, *Space Sci. Rev.*, 86, 357
- Su, Y., Holman, G. D., & Dennis, B. R. 2011, *ApJ*, 731, 106
- Thalmann, J. K., & Wiegelmann, T. 2008, *A&A*, 484, 495
- Thalmann, J. K., Wiegelmann, T., & Raouafi, N. 2008, *A&A*, 488, L71
- von Rosenvinge, T. T., Reames, D. V., Baker, R., et al. 2008, *Space Sci. Rev.*, 136, 391
- Vourlidas, A., Howard, R. A., Esfandiari, E., et al. 2010, *ApJ*, 722, 1522
- . 2011, *ApJ*, 730, 59
- Vourlidas, A., Subramanian, P., Dere, K. P., & Howard, R. A. 2000, *ApJ*, 534, 456
- Welsch, B. T., Li, Y., Schuck, P. W., & Fisher, G. H. 2009, *ApJ*, 705, 821
- White, S. M., Thomas, R. J., & Schwartz, R. A. 2005, *Sol. Phys.*, 227, 231
- Woods, T. N., Kopp, G., & Chamberlin, P. C. 2006, *Journal of Geophysical Research (Space Physics)*, 111, 10
- Woods, T. N., Eparvier, F. G., Bailey, S. M., et al. 2005, *Journal of Geophysical Research (Space Physics)*, 110, 1312
- Woods, T. N., Hock, R., Eparvier, F., et al. 2011, *ApJ*, 739, 59
- Woods, T. N., Eparvier, F. G., Hock, R., et al. 2012, *Sol. Phys.*, 275, 115